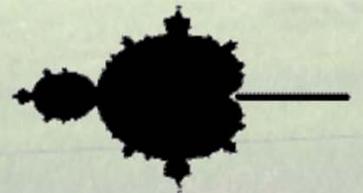# Exposure-based Wind Flow Modeling with a Single Met Site

Liz Walls and Jack Kline
RAM Associates

AWEA Wind Resource Seminar
Las Vegas, NV December 11, 2013

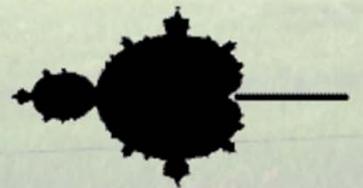**RAM** *Associates*

Resource Assessment & Micrositing

Audience Poll Questions

1. How often do you perform wind flow modeling?
   a. Never
   b. Occasionally (2 - 4 times/year)
   c. Frequently (2 – 4 times/month)

2. Are you familiar with exposure-based wind flow modeling?
   1. Not at all
   2. Somewhat familiar
   3. Very familiar

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Exposure Definition + Background

- Terrain Exposure: Summation of the elevation differences between a single point and the surrounding grid points within a specified radius weighted by the inverse of the distance between the two points.

$$\left(\underline{\hspace{2cm}} \right)$$

$$\left(\underline{\hspace{1.5cm}} \right)$$

- **Positive Exposure: Terrain slopes down**
- **Negative Exposure: Terrain slopes up**

DW > 0, UW < 0

DW < 0 UW > 0
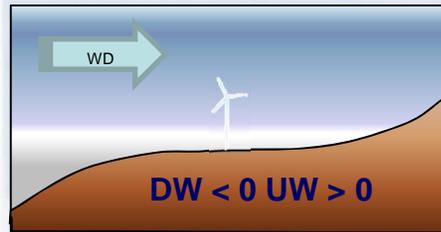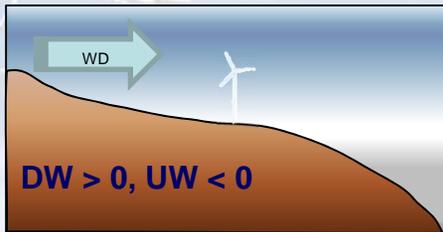
U.S. Patent 8,483,963: Method of evaluation wind flow based on terrain exposure and elevation Issued to Jack Kline 7/9/2013

Elevation at node, i, : Zi

$d_{zo} - d_{zi}$

Elevation at Met: Z_o

R
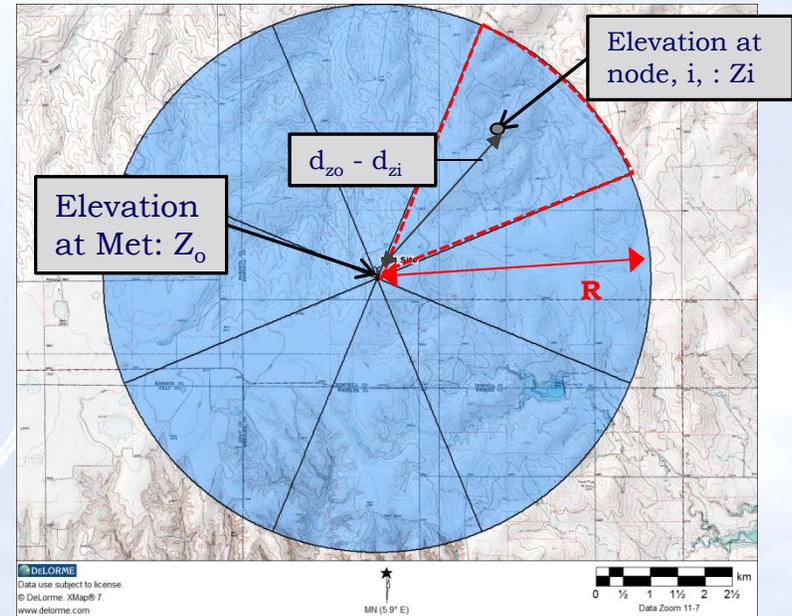
- Calculated in each sector and over range of radii
- UW Expo is weighted average of exposure and relative wind rose
- DW Expo is weighted average of exposure and DW relative wind rose
- Relative wind rose is wind rose combined with directional wind speed ratio

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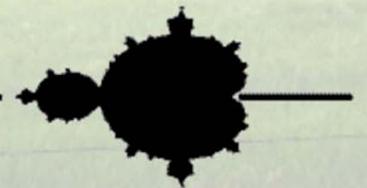
Resource Assessment & Micrositing
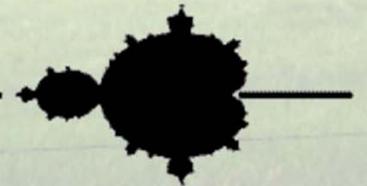
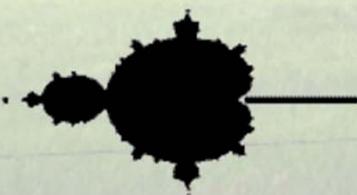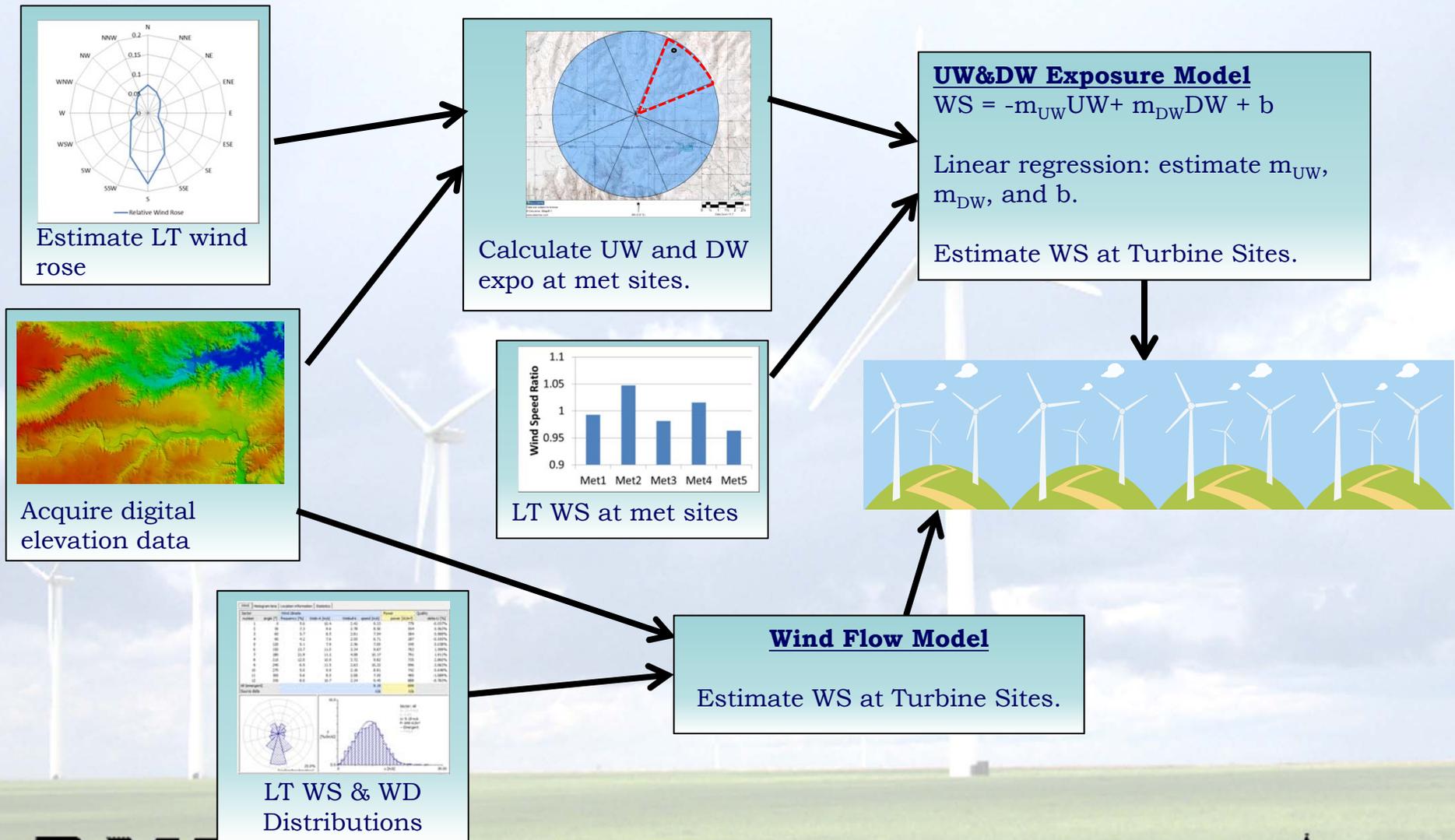# Previous Studies Involving Exposure-based modeling

- **A New and Objective Empirical Model of Wind Flow Over Terrain**
  - AWEA Wind Resource & Project Assessment Workshop 2007, Portland, OR
  - Presented by: Jack Kline, RAM Associates
  - First introduction of exposure-based modeling to the wind industry. The linear relationship that exists between wind speed and exposure was demonstrated.

- **Wind Flow Modeling Software Comparison**
  - AWEA Wind Resource Assessment Workshop 2009, Minneapolis, MN
  - Presented by: John Vanden Bosche, Chinook Wind
  - Wind flow model results were compared at two project sites with moderately complex terrain. The models included WAsP, CFD models and RAMWind (exposure) model. The RAMWind model produced the most accurate results.

- **Comparison of WAsP, MS-Micro/3, CFD, MWP, and Analytical Methods for Estimating Site-Wide Wind Speeds**
  - AWEA Wind Resource and Project Energy Assessment Workshop 2009, Minneapolis, MN
  - Presented by: David VanLuvanee, GEC-DNV
  - Wind flow model results were compared at four project sites with moderately complex terrain. The models included WAsP, CFD models and RAMWind (exposure) model. At three out of four sites, the RAMWind model produced the most accurate results.

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Typical Wind Flow Modeling Workflow

Estimate LT wind rose

Acquire digital elevation data

Calculate UW and DW expo at met sites.

LT WS at met sites

UW&DW Exposure Model
$$WS = -m_{UW}UW + m_{DW}DW + b$$

Linear regression: estimate m_{UW}, m_{DW}, and b.

Estimate WS at Turbine Sites.

LT WS & WD Distributions

Wind Flow Model

Estimate WS at Turbine Sites.

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UW&DW model

- Two-parameter linear relationship between wind speed and sensitivity of wind to UW exposure, m_{UW}, and sensitivity of wind to DW exposure, m_{DW}.

$$WS = -m_{UW}UW + m_{DW}DW + b$$

- There are 8 different scenarios represented by UW&DW model
- Ex 1: Scenario 4, DW>0, UW<0 so WS ++
- Ex 2: Scenario 8, DW<0, UW>0 so WS --

WD
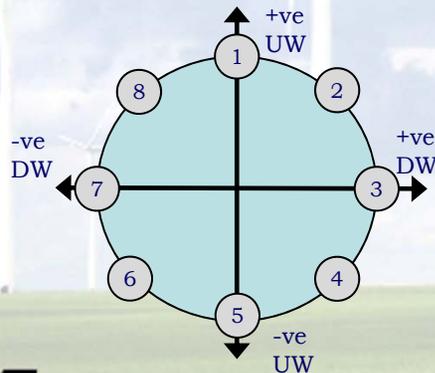
Scenario 1: DW ~ 0, UW >0
$WS = -m_{UW}UW + 0 + b$

WD

Scenario 2: DW = UW >0
$WS = (-m_{UW}+m_{DW})DW + b$

WD

Scenario 3: DW > 0, UW ~0
$WS = 0 + m_{DW}DW + b$

WD

Scenario 4: DW > 0, UW <0
$WS = -m_{UW}UW + m_{DW}DW + b$

WD

Scenario 5: DW ~ 0, UW < 0
$WS = -m_{UW}UW + 0 + b$

WD

Scenario 6: DW = UW < 0
$WS = (-m_{UW}+m_{DW})DW + b$

WD

Scenario 7: DW<0, UW~0
$WS = 0+m_{DW}DW + b$

WD

Scenario 8: DW<0 UW>0
$WS = -m_{UW}UW+m_{DW}DW + b$

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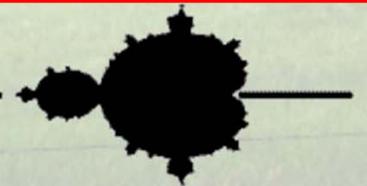
# What to do with only 1 or 2 mets?

- Many development sites only have 1 or 2 met sites which makes it impossible to establish a meaningful linear regression

- Reviewed exposure-based models developed at 12 different sites from across the US and Canada to see if there was a commonality.

- At each site, UW&DW models that produced an RMS error < 1% were established.

- At each site, the UW and DW coefficients were systematically varied and all models that produced an RMS error of < 1% were retained.

Is there a common denominator between UW&DW models?
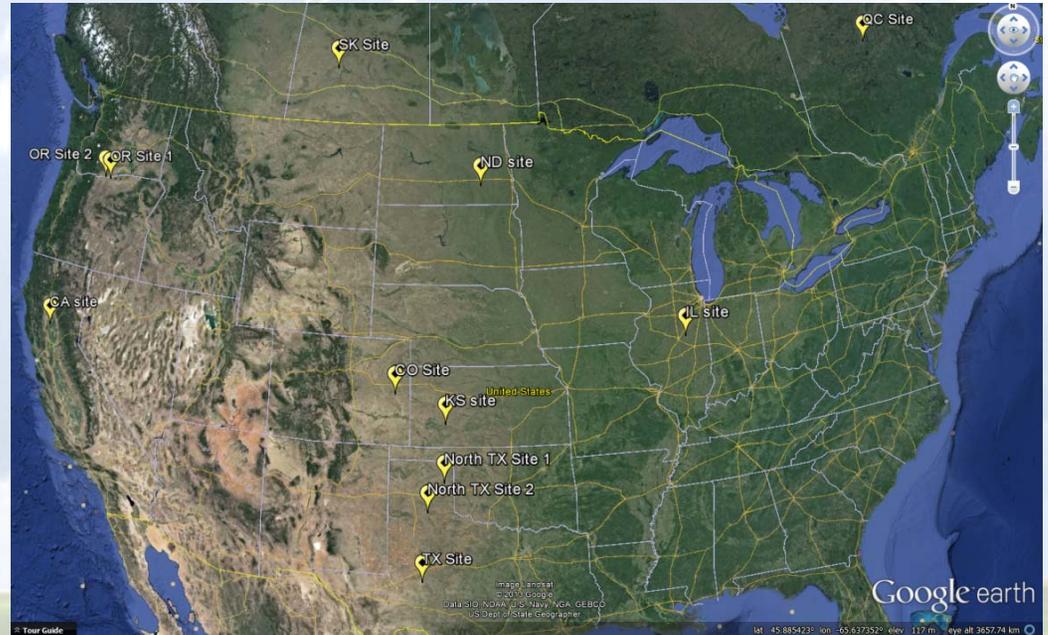
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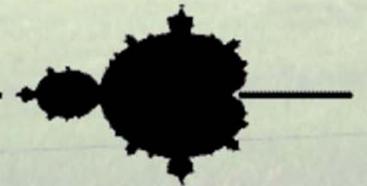
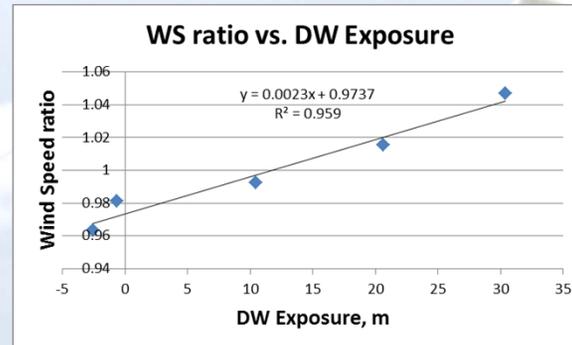# Examples of UW&DW models: Two Special Cases

- Since UW&DW is two-parameter linear regression, difficult to graphically demonstrate the linear relationship.
- Two special cases: UW&DW model reduces to one-parameter linear regression if $m_{UW} = 0$ or if $m_{UW} = m_{DW}$
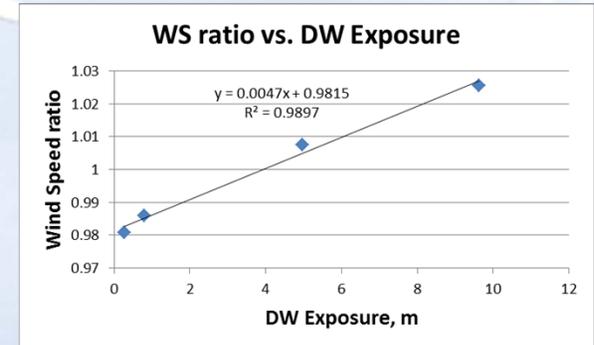
$$WS = -m_{UW}UW + m_{DW}DW + b$$

1. If $m_{UW} = 0$ Then
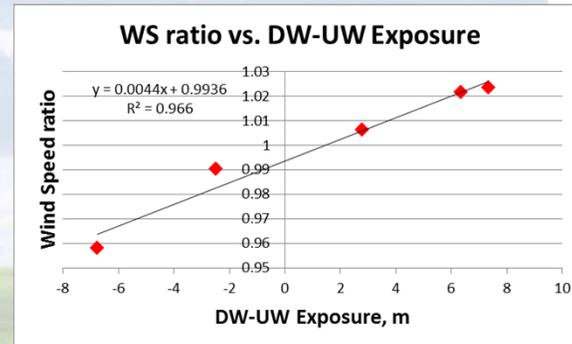   - $WS = m_{DW}DW + b$
   - Plot WS vs. DW

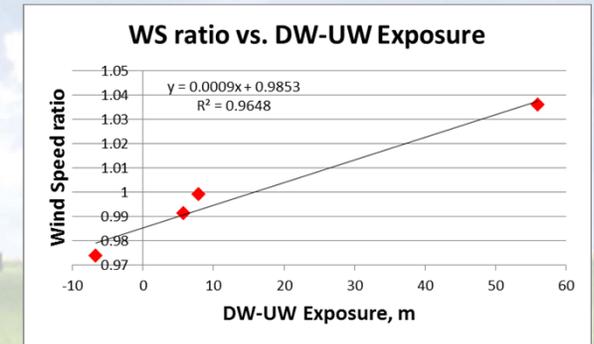2. If $m_{UW} = m_{DW}$ Then
   - $WS = m(DW-UW) + b$
   - Plot WS vs. DW-UW

UW&DW model from site in ND

WS ratio vs. DW Exposure

$y = 0.0023x + 0.9737$
$R^2 = 0.959$

UW&DW model from site in CO

WS ratio vs. DW Exposure

$y = 0.0047x + 0.9815$
$R^2 = 0.9897$
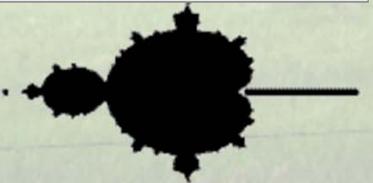
UW&DW model from site in TX

WS ratio vs. DW-UW Exposure

$y = 0.0044x + 0.9936$
$R^2 = 0.966$

UW&DW model from site in OR

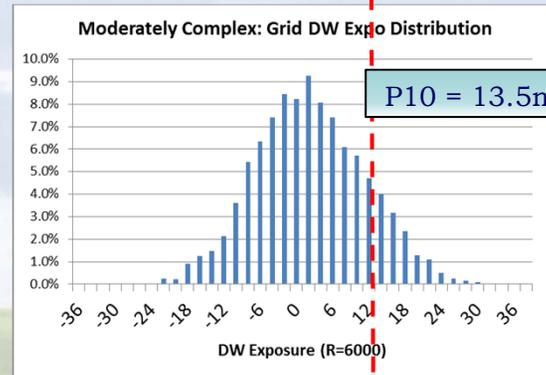**WS ratio vs. DW-UW Exposure**
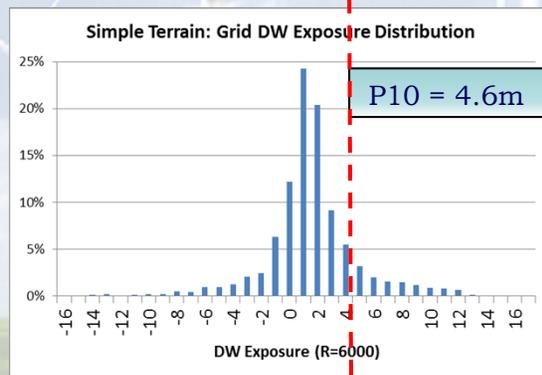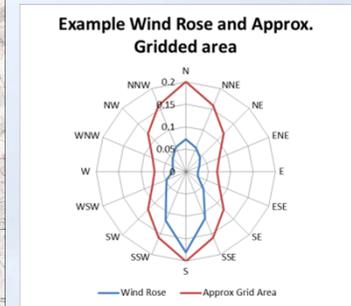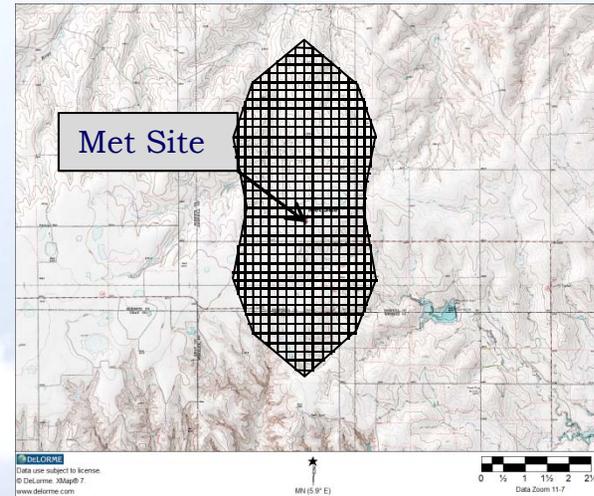
$y = 0.0009x + 0.9853$
$R^2 = 0.9648$

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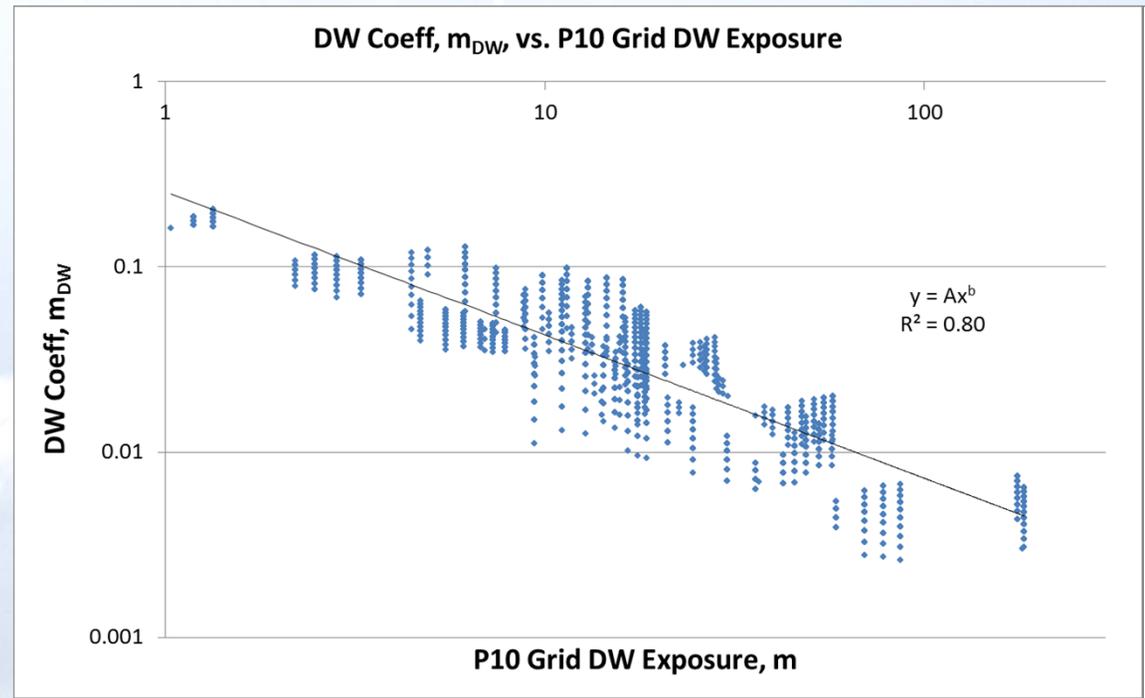
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Quantifying Terrain Complexity with P10 Grid DW Exposure

- To compare UW&DW models at different sites, needed a parameter that quantifies complexity of terrain.

- For each met used UW&DW models, created a grid that is shape of the wind rose and includes both UW and DW terrain.

- Exposures at nodes within the grid were statistically analyzed.

- Compared UW&DW coefficients to P10 Grid DW exposure at 12 sites.

Met Site

Example Wind Rose and Approx. Gridded area

— Wind Rose — Approx Grid Area

Simple Terrain: Grid DW Exposure Distribution

P10 = 4.6m

DW Exposure (R=6000)

Moderately Complex: Grid DW Expo Distribution

P10 = 13.5m

DW Exposure (R=6000)

Complex Terrain: Grid DW Expo Distribution

P10 = 142.3m

DW Exposure (R=6000)

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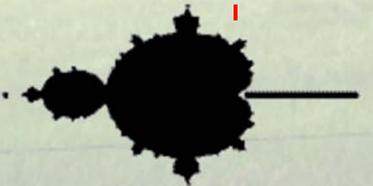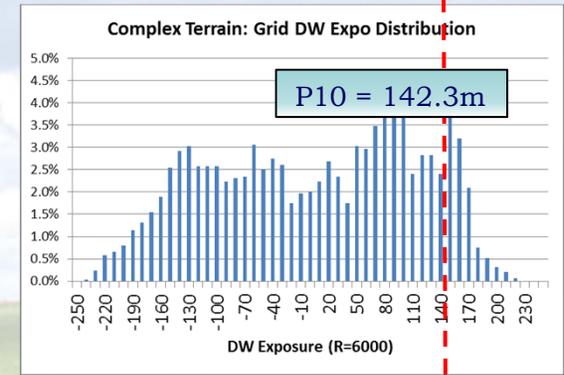
DW coeff., m_{DW}, vs. P10 Grid DW Exposure

- At 12 sites, varied UW and DW coefficients and developed UW&DW models over a range of radii and collected all with an RMS <1%

- Plotted the DW coefficient, m_{DW}, versus P10 grid DW exposure

- Found a power law relationship between the DW coeff, m_{DW}, and P10 grid DW exposure

DW Coeff, m_{DW}, vs. P10 Grid DW Exposure

$y = Ax^b$
$R^2 = 0.80$

DW Coeff, m_{DW}

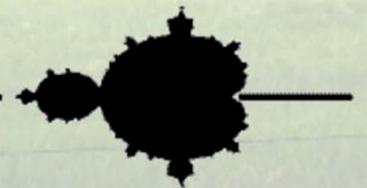P10 Grid DW Exposure, m

Low exposure = flat terrain
- WS is more sensitive to exposure variation.

High exposure = complex terrain
- WS is less sensitive to exposure variation.

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# UW coeff., m_{UW}, vs. P10 Grid Exposure

- Need method of estimating UW coefficient.
- $|m_{UW}|$ always less than m_{DW}
  - WS more sensitive to changes in DW exposure than changes UW exposure
- Observed that as $|P10\ DW - P10\ UW|$ gets larger, $|m_{UW}|$ approaches m_{DW}
  - Influence of UW terrain increases when difference between UW and DW terrain.
- Found another power law that relates coefficents, m_{UW} and m_{DW}.

$m_{DW} - |m_{UW}|$ vs. $|P10\ Grid\ DW - P10\ Grid\ UW|$

$R^2 = 0.682$

$|P10\ Grid\ DW - P10\ UW\ Exposure|$, m
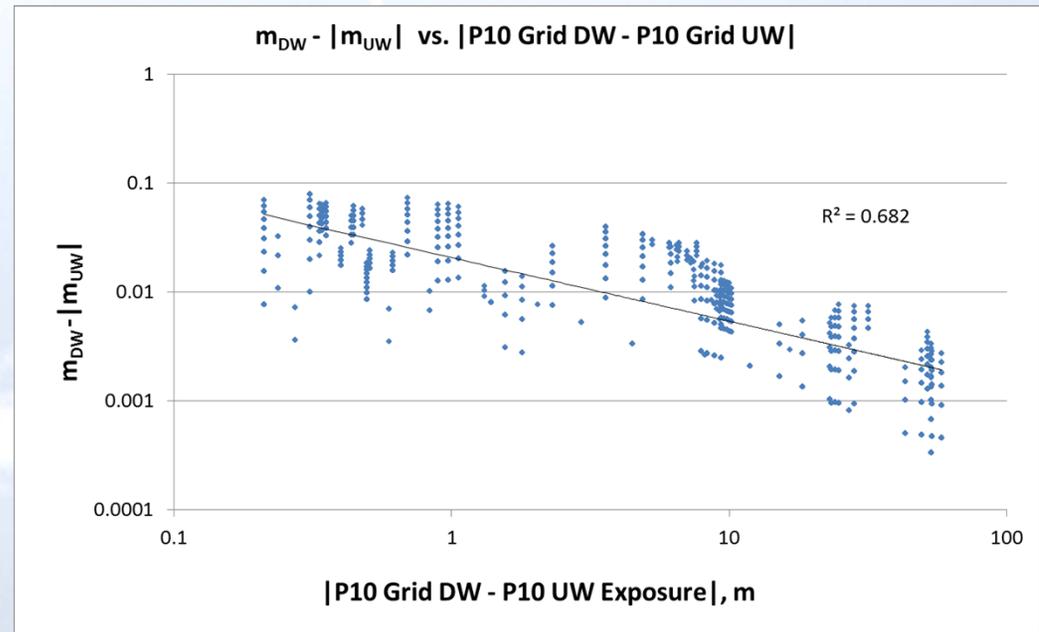
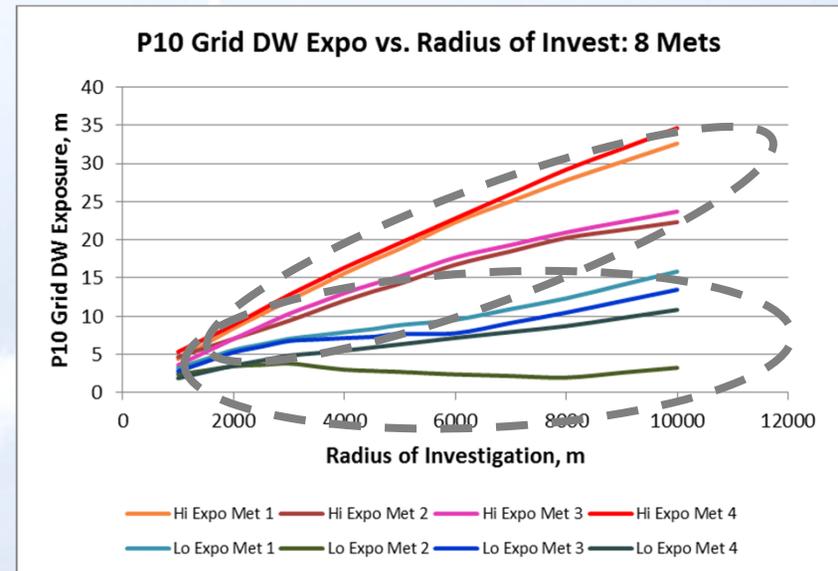With one met, we can now estimate m_{DW} and m_{UW} and use UW&DW model.

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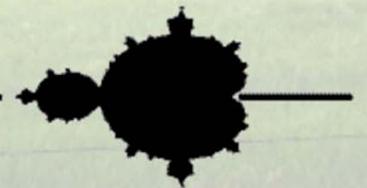
UW&DW Models and P10 Grid Exposure

- P10 Grid Exposure quantifies degree of terrain complexity and also serves as a comparison of terrain similarity.

- It was found that UW&DW models had best correlation and lowest error when mets had similar grid exposure statistics.

- When using an UW&DW model to estimate WS from one point to another, error is reduced by performing estimates in stepwise fashion.


P10 Grid DW Expo vs. Radius of Invest: 8 Mets

Legend:
— Hi Expo Met 1 — Hi Expo Met 2 — Hi Expo Met 3 — Hi Expo Met 4
— Lo Expo Met 1 — Lo Expo Met 2 — Lo Expo Met 3 — Lo Expo Met 4

Higher Expo Sites
UW&DW models, RMS<1%
Avg P10 DW Expo = 27 m
Avg m_{DW} = 0.053

Lower Expo Sites
UW&DW models, RMS <1%
Avg P10 DW Expo = 13 m
Avg m_{DW} = 0.067

➢ UW&DW coeffs (i.e. sensitivity of WS to exposure variation) decrease as terrain complexity increases
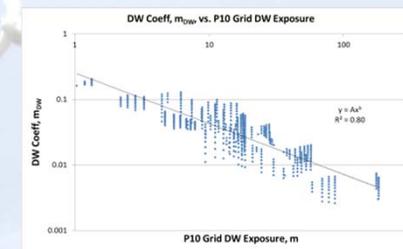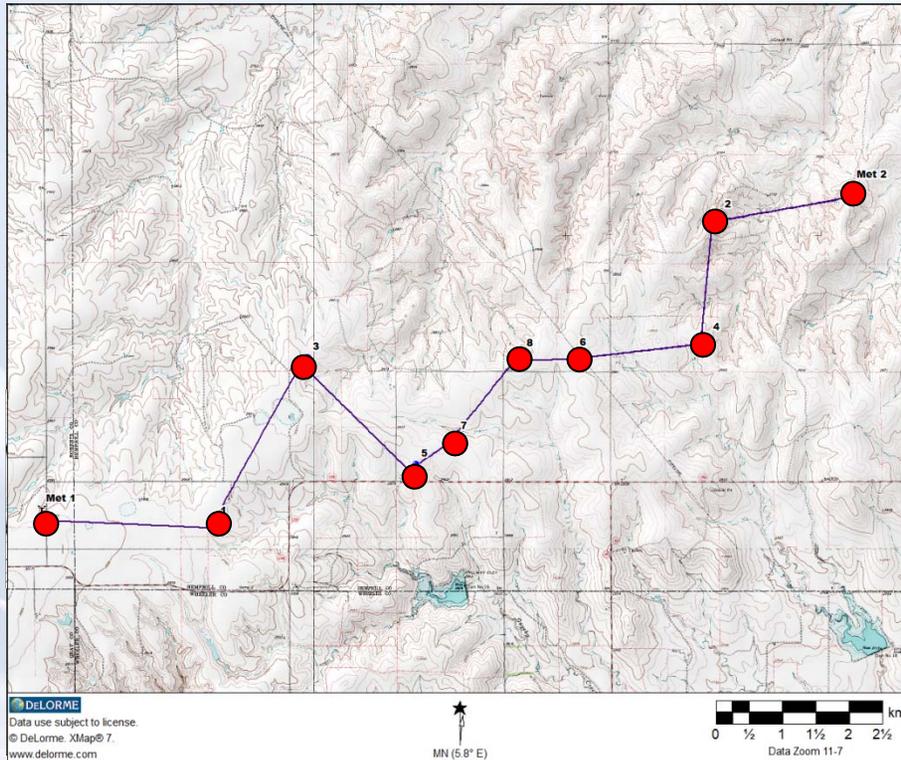
RAM Associates
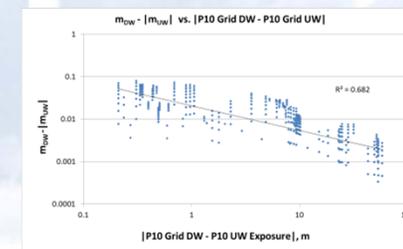Resource Assessment & Micrositing
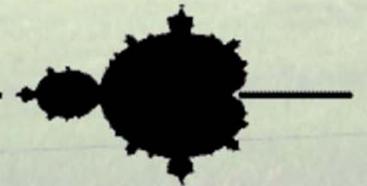
Using UW&DW model at a site with one met

- Compare grid stats between sites. If too different, create nodes until path from start to end node is found

- At each node, calculate P10 DW exposure and estimate m_{DW}
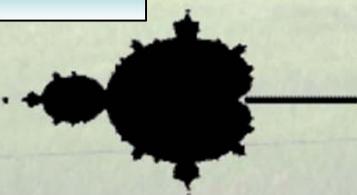

- And estimate m_{UW} from m_{Dw}:

- Calculate intercept, b, using WS and exposure from previous node (or met)

- Estimate WS using UW&DW Model: $WS = -m_{UW}UW + m_{DW}DW + b$

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Results: Stepwise UW&DW Single Met Model at 12 sites used in model development

- Using the same met sites from the 12 project areas that were used in model development, tested Stepwise Single Met UW&DW model:
  - ➢ Used each met as the predictor and estimated each of the other met sites.
  - ➢ Used stepwise approach to find path of grid nodes with similar terrain in between met sites.
  - ➢ Estimated UW&DW coefficients using power law relationships at each node.
  - ➢ Estimated wind speed along path from predictor met to target met sites.

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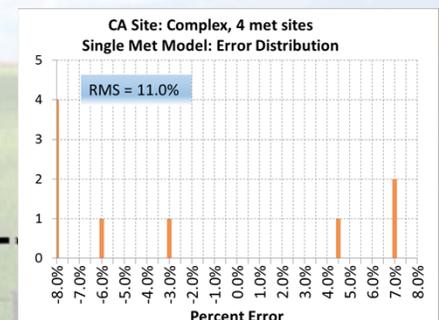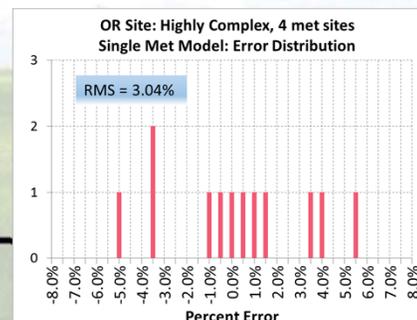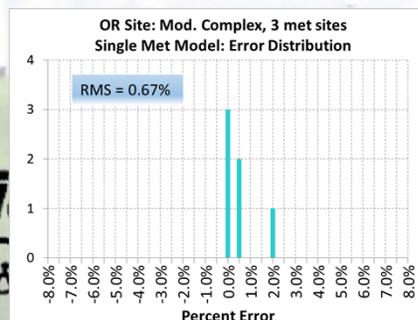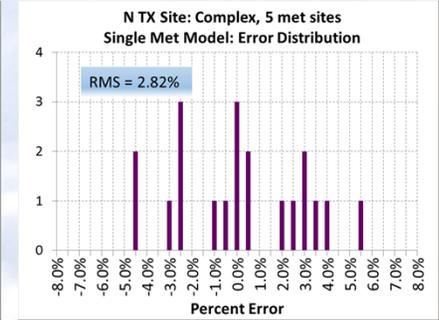
Resource Assessment & Micrositing
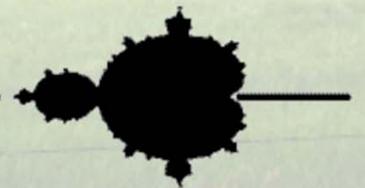
Error Distribution at 12 sites used in model dev.: Single Met Model Results

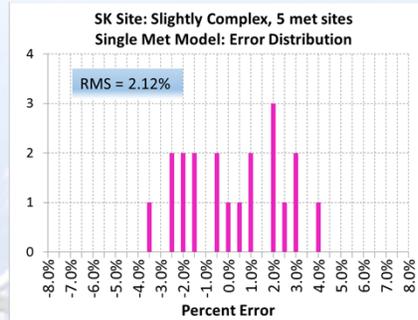| Site	# Mets	Terrain Desc.	RMSE
KS	5	Simple	0.80%
IL	8	Slighlty Complex	1.83%
CO	4	Slighlty Complex	1.93%
SK	5	Slighlty Complex	2.12%
N TX	6	Complex	1.18%
ND	5	Mod. Complex	2.00%
QC	4	Complex	2.77%
S TX	4	Mod. Complex	3.04%
N TX	5	Complex	2.82%
OR	3	Mod. Complex	0.67%
OR	0	Highly Complex	3.04%
CA	0	Complex	11.0%

Avg Simple/Slightly Complex	1.67%
Avg Mod. Complex/Complex	2.08%
Avg Highly Complex	3.04%

- **Single Met Model produced good to excellent results at 11 out of 12 sites.**
- **Have hypothesis regarding the CA site and reason for large errors.**

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KS Site: Simple terrain, 5 met sites — Single Met Model: Error Distribution — RMS = 0.80%

IL Site: Slightly complex, 8 met sites — Single Met Model: Error Distribution — RMS = 1.83%

CO Site: Slightly complex, 4 met sites — Single Met Model: Error Distribution — RMS = 1.93%

SK Site: Slightly Complex, 5 met sites — Single Met Model: Error Distribution — RMS = 2.12%

North TX Site: Complex, 6 met sites — Single Met Model: Error Distribution — RMS = 1.18%

ND Site: Moderately complex, 5 met sites — Single Met Model: Error Distribution — RMS = 2.00%

QC Site: Complex, 4 met sites — Single Met Model: Error Distribution — RMS = 2.77%

South TX Site: Mod. Complex, 4 met sites — Single Met Model: Error Distribution — RMS = 3.04%

N TX Site: Complex, 5 met sites — Single Met Model: Error Distribution — RMS = 2.82%

OR Site: Mod. Complex, 3 met sites — Single Met Model: Error Distribution — RMS = 0.67%

OR Site: Highly Complex, 4 met sites — Single Met Model: Error Distribution — RMS = 3.04%

CA Site: Complex, 4 met sites — Single Met Model: Error Distribution — RMS = 11.0%

Two Met Stepwise UW&DW Adaptable Model

- When two met sites are available for modeling, an adaptable UW&DW model can be used to reduce the wind speed estimate error.
  - Adaptable -> UW&DW coefficients are adjusted to reduce error.
- At 12 sites, with each pair of mets:
  - Wind speed estimates are cross-predicted between met sites and the UW&DW coefficients are systematically modified until the cross-prediction error reaches < 1%.
  - The "site-calibrated" UW&DW model is then used to predict at all the other sites.

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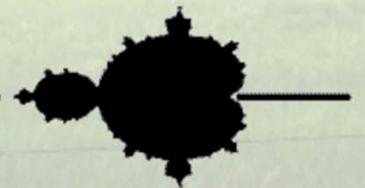
Error Distribution at 12 sites used in model dev.: Two Met Model Results

| Site	1-Met	2-Met	Error Diff.
KS	0.80%	0.69%	-0.11%
IL	1.83%	1.69%	-0.14%
CO	1.93%	1.78%	-0.15%
SK	2.12%	1.67%	-0.45%
N TX	1.18%	1.16%	-0.02%
ND	2.00%	1.62%	-0.38%
QC	2.77%	2.81%	0.04%
S TX	3.04%	2.91%	-0.13%
N TX	2.82%	1.48%	-1.34%
OR	0.67%	-	-
OR	3.04%	2.71%	-0.33%
CA	11.0%	-	-

Avg Simple/Slightly Complex	-0.21%
Avg Mod. Complex/Complex	-0.37%
Avg Highly Complex	-0.33%

- **Two Met Model reduced RMS error at all but one site.**
- **Further improvements are expected as more mets added.**

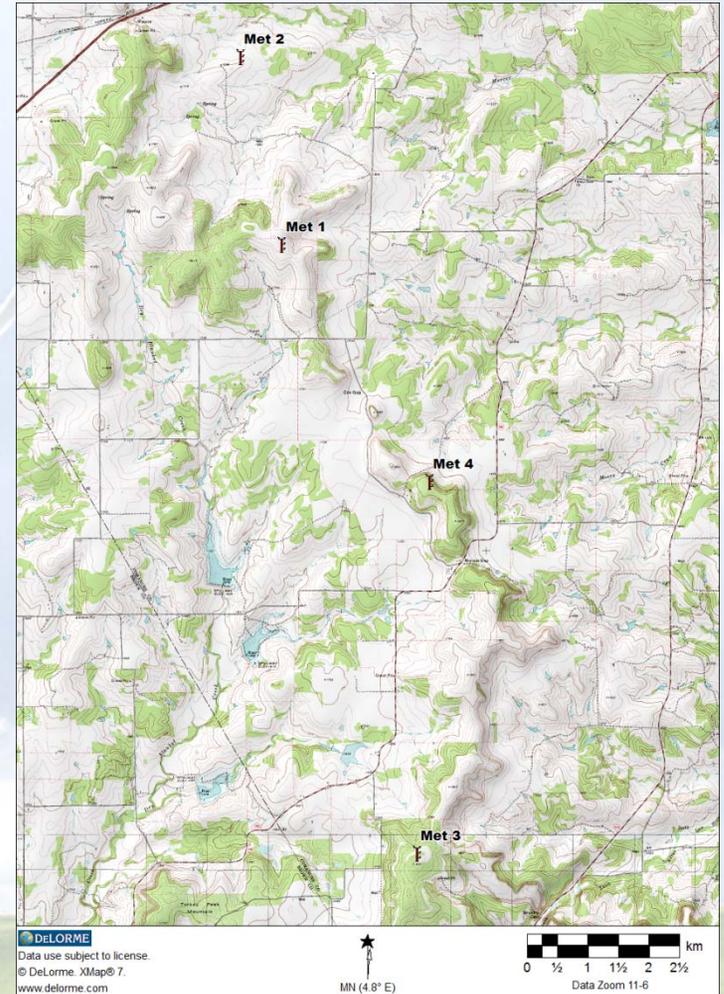**RAM Associ**

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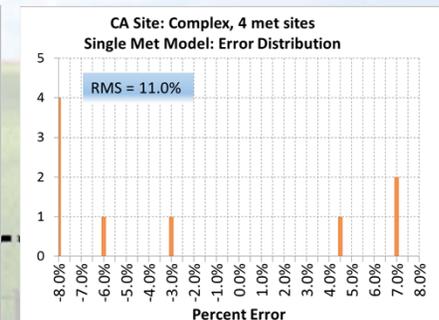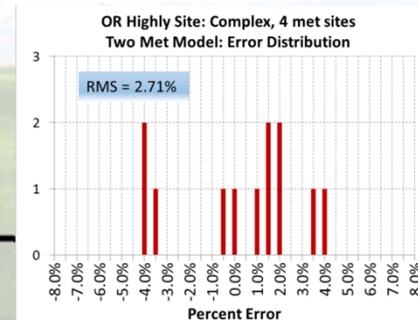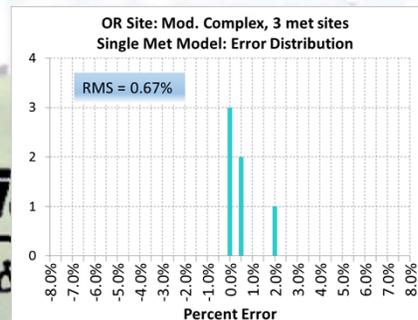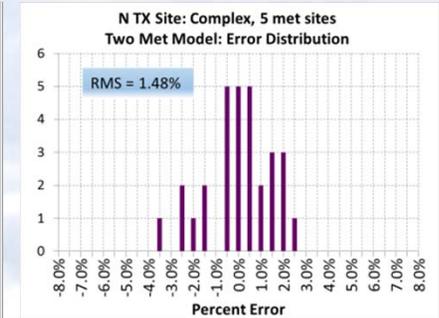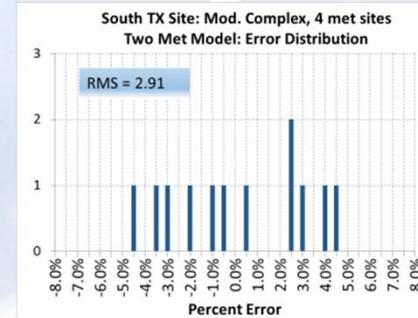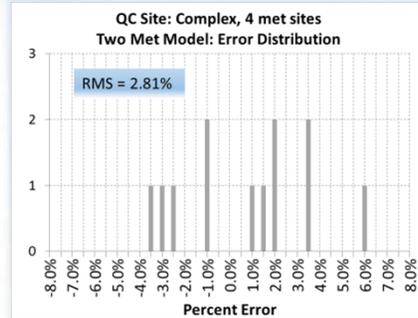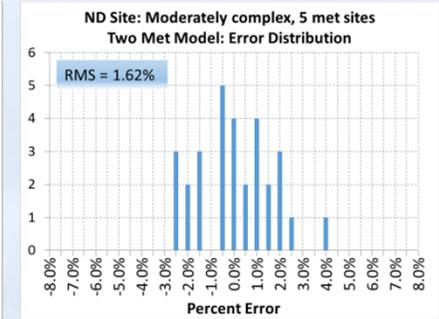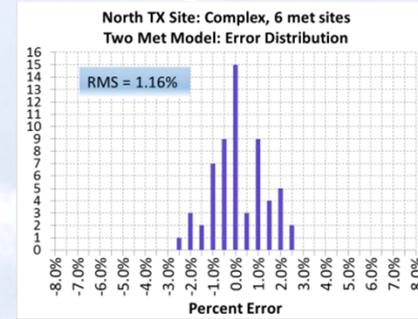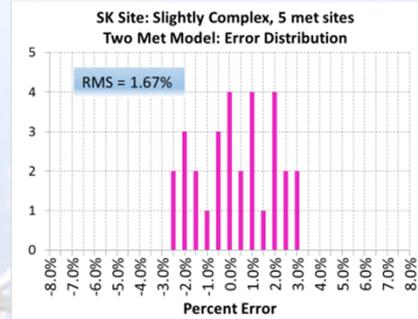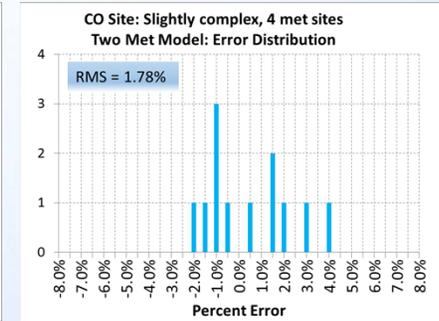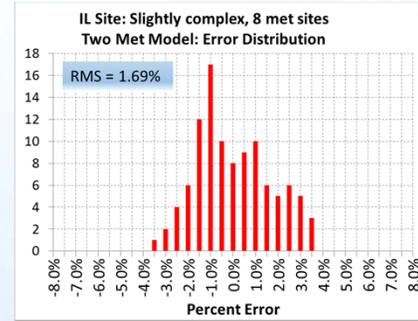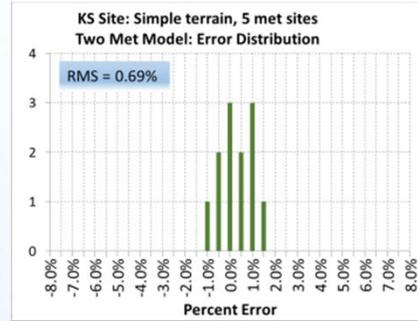
Case Study: UW&DW Model at N. Texas Site (not used in model development)

- 4 mets at site in N Texas
- Estimated LT 80 m WS at each site
- Used Single Met Stepwise UW&DW to cross-predict WS.

DW Exposure at Mets vs. Radius of Inv.

UW Exposure at Mets vs. Radius of Inv.
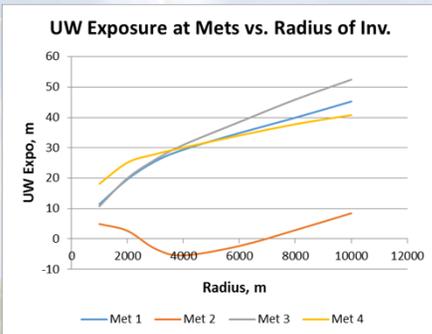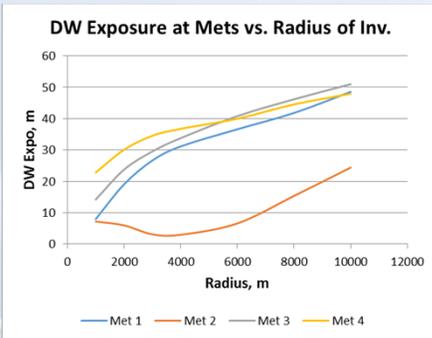
Met	80m WS ratio	Elev, m
1	1.000	558
2	0.958	520
3	1.003	564
4	0.999	552

Predictor	Predictee	Error, %
Met 1	Met 2	1.12%
Met 1	Met 3	0.65%
Met 1	Met 4	1.95%
Met 2	Met 1	-0.61%
Met 2	Met 3	-0.49%
Met 2	Met 4	-0.74%
Met 3	Met 1	-0.66%
Met 3	Met 2	1.08%
Met 3	Met 4	1.26%
Met 4	Met 1	-1.95%
Met 4	Met 2	3.15%
Met 4	Met 3	-1.26%

RMS	1.45%

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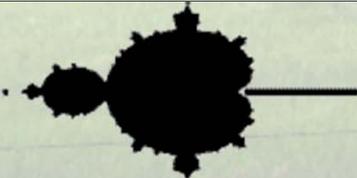
Conclusions

1. Defined generic UW&DW exposure-based model
   - Found common relationship between UW&DW coefficients and exposure at 12 sites across North America.
   - WS estimates can now be generated with a single met site.

2. Introduced Stepwise method where WS is estimated along path of nodes
   - Since UW&DW coefficients vary with grid exposure, stepwise method reduces error by estimating wind speeds along nodes with similar terrain.

3. UW&DW model can be "site-calibrated" to further reduce error
   - With two or more mets, the coefficients can be adjusted such that error is minimized.
   - RMS can be reduced after UW&DW model is adjusted for site-specific coefficients.

Currently, working on incorporating Stepwise Adaptable UW&DW Model into RAMWind 2.0

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